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EFFECT OF INJECTION PRESSURE AND TIMING ON BIODIESEL FUELLED ENGINE

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ABSTRACT

An experimental matrix was designed to optimize a VW CIDI to run on biodiesel by examining the influence of injection timing only, injection pressure only and their combined influence on fuel consumption and emissions of CO, HC and NOx. Injection timing was varied at six (6) levels including advance of 9^0, 6^0, 3^0 and retardation of 6^0 and 3^0 while the engine default timing was kept at 0^0. Injection pressure was varied at five (5) levels from 150 to 250 bar in steps of 25 bar. Generally higher injection pressures produced lower fuel consumption. For PKOME and COME, an injection pressure of 250 bar and an injection advance of 3^0 were found with the lowest fuel consumption and least exhaust emissions. The optimal values for JCME were found to be at injection pressure of 200 bar and injection timing of 3^0.

KEYWORDS: Injection Timing, Injection Pressure, Biodiesel, Renewable Energy, Automotive, Alternative Fuels

INTRODUCTION

Increasing industrialization of the world has led to a rise for the demand of petroleum-based fuels [1]. Today fossil fuels take up 80% of the primary energy consumed in the world, of which 58% alone is consumed by the transport sector [2]. It has been estimated that oil production will show a downward trend to become just 35% of today's production by the year 2075 [3]. According to the International Energy Agency, from 2000 through 2008, global diesel (also called gasoil or distillate in some parts of the world) consumption increased by 23%, while consumption of other petroleum products grew by 7%. This is because mostly petrol has just one application as fuel for transport, while diesel has a number of applications. Diesel fuel is used also in industries such as the mining industries and homes to power generators. For the reasons aforementioned, this research is focussed on an alternative to conventional petroleum diesel (also petro diesel), biodiesel.

The sources of fossil fuels are becoming exhausted and are found to be major contributors to greenhouse gas (GHG) emissions. Consumption of fossil fuels leads to many negative effects including climate change, receding of glaciers, rise in sea level, loss of biodiversity [4]. Reduction of engine emissions is a major research aspect in engine development with the increasing concern on environmental protection and the stringent exhaust gas regulation. Biodiesel is a renewable, domestically produced fuel that has been shown to reduce particulate, hydrocarbon, and carbon monoxide emissions from diesel engines. Biodiesel obtained from energy crops produces favourable effects on the environment, such as a decrease in acid rain and in the greenhouse effect caused by combustion. Biodiesel for instance exhibits a 41% decrease in greenhouse gas emissions compared to diesel fuel [5]. Typical biodiesel produces about 65% less net carbon monoxide, 78% less carbon dioxide, 90% less sulphur dioxide and 50% less unburnt hydrocarbon emission [6-9]. The results of this research will be significant in the usage of biodiesel in compression ignition engines. It will provide optimum injection timings that will aid Engineers in the vehicle industry. Mofijur et al [10] have stated in their work that

only the oxidation stability of B10 and B20 meet the European specifications (EN 590) of 20 h. Therefore, only B10 and B20 have been used to evaluate engine performance and emission. This is evident in Table 1.

Table 1: Work Done on the three Feed Stocks So Far

Feedstock	Proportion	Engine Tested	Methodology	References
PKOME	B100	no engine tests conducted	Biodiesel production	[1,2,3,4,5,6,7,8,9]
COME	B20 B100	4-cylinder diesel engine No engine tests	Emissions test, BSFC Properties	[10,11,12,13] [14,15,16,17,18]
JCME	B20 and B50 B100 B100	Engine tests No engine tests Engine tests	Engine performance Emissions	[19, 20,21,22,23,24] [25]

In the case of PKOME no engine runs have been conducted let alone engine optimisation. Engine runs have been conducted for COME but only up till B20 and no further research of B100 have been conducted. This is the same for JCME where engine runs have been up till B50. Only Bhupendra et al. [11] conducted engine runs on B100, however they failed to conduct engine optimisation tests.

When diesel is completely replaced by biodiesel it is apparent that engine modifications are required. This is to avoid degradation in engine performance, pollution and engine durability issues. NOx is known to increase with the use of biodiesel. Torque, power and brake thermal efficiency will all decrease significantly with biodiesel usage. Brake specific fuel consumption and brake specific energy consumption will all increase making it more expensive to use biodiesel. In the case of no modification to an engine, the injection feature of biodiesel is influential to engine power. It is necessary to further research the relationship between injection pressure and injection timing and engine power in order to obtain the optimal match when using biodiesel [12]. Biodiesel engine economy is affected by engine type and its operating conditions, such as load, speed, and injection timing and injection pressure. Engine operating conditions, such as load, speed, injection timing and pressure are also influential to biodiesel engine economy. Further study on these conditions should be executed to improve engine and its control systems in order to obtain the optimal match. The kinematic viscosity of biodiesel is higher than diesel fuel and this affects fuel atomization during injection and requires modified fuel injection systems [13]. This is confirmed by Xue at al. [14] when the recommended that engine control should be readjusted and/or redesigned for biodiesel systems especially for optimizing ignition and injection. So the focus of work from onward should be development of 100% biodiesel and not biodiesel-petrodiesel blends [15]. This work therefore also investigates the effect of injection timing, injection pressure and their combined effect on engine performance of coconut, palm kernel and Jatropha oil biodiesel. It further provides optimization parameters for each feedstock chosen.

There is significant effect of injection timing on engine performance [16]. For increase of power and thermal efficiency, some recommendations for modifications in the engine operating parameters have been suggested. Compression ratio [17], injection process and parameters [18] have been found to affect the engine power and efficiency while using B100. Injection parameters have been reported to likely affect fuel consumption, power, torque and NOx formation. This is because of the different fuel properties of biodiesel, density, viscosity, bulk modulus, cetane number, oxygen content require different injection timing from that of conventional diesel [19]. Various researchers have shown

that the physical properties of density, viscosity, and isothermal compressibility strongly effect injection timing, injection rate and spray characteristics. This is confirmed by Payri et al. [20] who mention that in diesel engines, differences in physical properties of fuels could change the injection mechanism, the fuel spray behaviour, the combustion performance and consequently have an effect on pollutant emissions.

MATERIALS AND METHODS

Fuel Preparation

The procedure was carried out for all vegetable oils (Palm kernel oil, Coconut oil and Jatropha curcas oil) considered in this work. Acid-catalysed (Trans) esterification requires a much longer time than alkali-catalysed Trans esterification. This is why base-catalysed (Trans) esterification is used in this work. A Two-step process was used in the production of biodiesel. An alkaline-catalysed esterification using NaOH to convert FFAs in coconut oil to methyl esters to reduce FFA was carried out for an hour. In the second step acid-catalysed Trans esterification was carried out where the pre-treated oil were then converted to methyl ester to further reduce FFA and hence the viscosity.

Both esterification and (Trans) esterification were conducted in a laboratory-scale experiment. The raw vegetable oil (200g) was pre-heated for an hour to ensure removal of water as a precaution of the oil probably not being well prepared. The pre-heating was terminated when visual inspection showed there were no more bubbles. For all test runs for the variations, temperature was kept constant and stirring was at same speed. Methanol mixed with NaOH was added to the pre-heated vegetable oil mixture in the flat bottom reaction flask and stirred for an hour. The mixture was stirred for some time at the same rate and time for all test runs. In the second step H2SO4 was added to the pre-treated mixture and quickly stirred for about an hour. The essence of adding H2SO4 was to further reduce FFA and hence the viscosity of the biodiesel. Wet washing was then carried out with hot distilled water at 60oC and then dried to obtain the biodiesel. The same procedure was carried for Palm kernel oil and Jatropha oil.

Equipment and Materials

The procedure was carried out for all vegetable oils (Palm kernel oil, coconut oil, Jatropha oil). Injection timing was varied at five (6) levels including a retardation of 6^0C, 3^0C and advance of 6 ^{0}C, 3^0C, 9^0C and the engine default considered to be 0^0C. The Injection pressure was varied at five (5) levels from 150 to 250 bar in steps of 25 bar.

Experimental Set-Up

- A 4-cylinder VW diesel engine set-up was used as specified in Table 2

Table 2: Specifications of Engine Used

Engine Specification	Details
Engine make	VW Golf 3 water-cooled
Bore x Stroke	79.5x95.5mm
Aspiration	Turbo
Rated power	55kW
Rated speed	4200rpm
Compression ratio	22.5
Injection timing	336^0 CAD
Injection pressure	150 bar
Fuel type/system	Diesel/Bosch
Engine size/cylinders	1.896cm^3/4cylindes
Engine dynamometer	Alternator with water heaters

- Exhaust gas composition was measured using AVL 5 gas exhaust gas analyser (Make: AVL Austria; Model: TG DiGas 5400). This analyser measures CO2, CO, HC, NOx and O2 in the exhaust gas. The measurement range and accuracy of the exhaust gas analyser are given in Table 3.

Table 3: Measurement Range of Exhaust Analyser Used

Exhaust Gas Analyser		
Exhaust Gas	**Measurement Range**	**Accuracy**
CO	0-10 % vol.	<.06 vol.%:±0.03 vol.% P0.6 vol.%:±5% of ind. val.
HC	0-20,000 ppm vol.	<200 ppm vol.:±10 ppm vol.
NO	0-5000 ppm vol.	P500 ppm vol.:±10% of ind. val.

- Bosch standard nozzle tester (0-400 bar) with each graduation representing 2 bar was used to measure injection pressures on the nozzles.
- Variable 24 Pc. Diesel fuel injector pressure adjustment shim washer kit to adjust injection pressures

Factorial Design

Title of the article should be centred, with 22pt Times Two engine parameters, Injection Timing and Injection Pressure variations were considered to optimize engine performance in terms of emissions and fuel consumption for PKOME and COME. The results were obtained through a full scale laboratory experiment described in the experimental procedure. JMP software, version 10, was used to Design the experiment and at the same time analyse the results (Table 4).

Responses include

- Brake specific energy consumption (BSEC)
- Carbon monoxide (CO)
- Total Hydrocarbon (HC)
- Oxides of Nitrogen (NOx)

Factors

- Injection timing
- Injection pressure

Experimental Procedure

Each of the experiments explained below were replicated three times for each of the biodiesel fuels (PKOME, COME and JCME). Measurements were also taken of petroleum diesel, but these were done at the default values of injection pressure and timing as specified in the manufacturer's manual. The values given in this study are the average of the three results. All data were collected after the engine was sufficiently warmed up for each test, and the engine oil temperature was maintained around 65– 70 ^{0}C.

Injection timing was altered by adjusting the number of shims under the seat of the Injection pump mounting flange. This is done as follows

- The Top Dead Centre (TDC) position on the flywheel was located. This was done by raising piston to the top of the cylinder. The flywheel was then marked just when the piston got to the topmost position.
- As per the manufacturer's manual, the flywheel was turned slowly anticlockwise until the marked position in step 1 aligned perfectly with the alignment mark on the cylinder block. This determined the original static injection timing and compared very well with that in the manufacturers manual. The recommended fuel injection timing was 24^0BTDC or 336^0CAD with three shims.
- Emissions and fuel consumption measurements were made at this injection timing at separate injection pressures of 150, 175, 200, 225 and 250 bar.
- Extra shims of 0.3mm thickness were either added to retard or removed to advance the timing. The spill method was used to verify injection timing for each shim combinations.
- The fuel injection timing was further varied at 3 and 6 angle degrees retard. Each angle the timing was retarded engine emissions and fuel consumption measurements were taken.
- The procedure was repeated for injection advance of 3, 6 and 9 angle degrees.

Injection Pressure

Fuel consumption and emissions measurements were taken at injection pressures of 150, 175, 200, 225 and 250 bar. Variable 24 Pc. Diesel fuel injector pressure adjustment shim washer kit was used to adjust injector pressures. This was done by inserting or removing shims under nozzle spring until the required pressures were obtained. A metric digital calliper was used to measure thickness of hardened shims needed to obtain required pressure. Bosh standard nozzle tester (0-400 bar range) with accuracy of 2bar was used to test the varying pressures.

RESULTS AND DISCUSSIONS

Palm kernel oil methyl ester (PKOME) was characterised together with petroleum diesel according to the ASTM D6751 standard. Table 4, shows the properties of PKOME obtained in comparison with petroleum diesel and international standards.

Table 4: Results of Optimized PKOME Characterisation

Properties	PKO ME	Petrodiesel	ASTM D6751	EN 14214
Kinematic Viscosity @ 40^0C (mm^2/s)	3.7	2.6	1.9-6	3.5-5
Cetane number	50	49	47min	51min
Pour point (^{0}C)	1	1	-15 to 6	-
Cloud point (^{0}C)	6	2	-	-
Flash point (^{0}C)	170	90	93min	120min
High calorific value (MJ/kg)	44	46	-	35
Acid value (mol. %)	3.4	0.17	0.5 max	0.5 max
Density (kg/m^3)	878	839	880	860-900

Compared to published works, these are the best properties of PKOME obtained [21-24]. These results has been a result of optimized (Trans) esterification process. Viscosity of PKOME compares very well with petroleum diesel and passes the two major international standards for biodiesel (ASTM D6751 and EN14214). Viscosity is the major reason

why transesterification is necessary [25]. The viscosity of crude palm kernel oil measured was 29mm2/s compared to palm kernel oil biodiesel of 3.7mm2/s. If fuel viscosity is too high, it may cause too much pump resistance, filter damage, poor combustion, increased exhaust smoke and emissions [26]. In general, higher viscosity leads to poorer fuel atomization [27]. Viscosity of PKOME is still slightly higher than petroleum diesel and this is reported in literature that biodiesel has higher viscosity compared to Petroleum diesel due to high fatty acid composition [28, 29]. Fatty acid composition determines the degree of saturation and the higher the composition the higher the degree of saturation. Viscosity increases with increasing degree of saturation.

Cetane Number (CN), a dimensionless parameter, is a measure of fuel quality is vital in determining whether a fuel is suitable for use in a compression ignition engine. The best CN obtained for PKOME as a result of the optimization was 50 compared to petroleum diesel of 49 and met both ASTM and EN standards. The longer the fatty acid carbon chains the more saturated the molecules, the higher the CN [30]. Since biodiesel is largely composed of long-chain hydrocarbon groups (with virtually no branching or aromatic structures) it typically has a higher CN than petroleum diesel.

Flow properties such as pour point (PP) and cloud point (CP) are important in determining performance of fuel flow system. Viscosity is known to be influenced strongly by temperature and is inversely proportional. Operating a diesel engine at low temperatures especially in cold climate regions can be difficult because of high viscosities. This is why low temperature properties are necessary to determine feasibility of use in cold countries. The temperature at which cloud wax crystals first appear in the oil when it is cooled is termed cloud point. This is usually visible to the naked eye. The cloud point obtained for PKOME (60C) compares very well with petroleum diesel (20C) though there are no specified limits prescribed for both ASTM and EN standards. Pour point obtained for both PKOME and petroleum diesel were the same at 10C. This implies that the lowest temperature at which both palm kernel oil biodiesel (obtained in this work) and petroleum diesel can be poured is the same. Calorific value also lower/upper heating values can be used to distinguish among different fuels their likelihood to produce more or less power or torque per the same volume. It compares the energy content per litre for the various fuels under consideration. At 44MJ/kg palm kernel oil biodiesel is close to petroleum diesel (46MJ/kg) and meets the standards. Compared to Petroleum diesel, biodiesel has been generally reported to have lesser Heating value [13].This is because for biodiesel, carbon and hydrogen are the sources of thermal energy while oxygen is ballast. Petroleum diesel fuel is made up of a mixture of various hydrocarbon molecules and contain little oxygen (less than 0.3%), while biodiesel contain significant amount of oxygen (9%). Hence due to its high oxygen content, biodiesel has lower Heating values than petroleum diesel [31]. Except combustion efficiency of biodiesel will be higher, due to the higher oxygen content. This presupposes that the stoichiometric air/fuel ratio of biodiesel will be lower than that of diesel because lesser air will be required to burn biodiesel compared to conventional diesel. This is why some level of modification is required in a diesel engine for optimum operation of biodiesel. It is also for this same reason that many have reported higher NOx emissions for biodiesel fuelled engines [32-35].

Acid value is a measure of auto-oxidation, storage stability or mental contamination [36]. The acid value for PKOME is higher than petroleum diesel but falls within the required limits. However, it is an indication that PKOME is more unstable compared with petroleum diesel.

The results show the Density of PKOME (878kg/m3) exceeds that of petroleum diesel (839kg/m3) but well within the standards. It has been generally reported that biodiesel has a higher density than petroleum diesel. This is why biodiesel is considered already ‘chemically advanced’ in terms of injection timing (Caresana, 2011). Implying for the same engine it

will take a shorter time for biodiesel compared to petroleum diesel to travel from injection pump to the injector. The high density hence compensates for the lower calorific or heating value.

Engine Optimization for PKOME Engine

An experimental matrix was designed with the help of JMP 10 to analyse the influence of injection timing only, injection pressure only and their combined influence on fuel consumption and emissions of CO, HC and NOx. Brake specific energy consumption (BSEC) was chosen compared to brake specific fuel consumption (BSFC) because it is a better method of comparing energy contents in fuels. From Figure 1, the result show that injection advance lowers the fuel consumption while a retardation increases fuel consumption for an engine fuelled with PKOME.

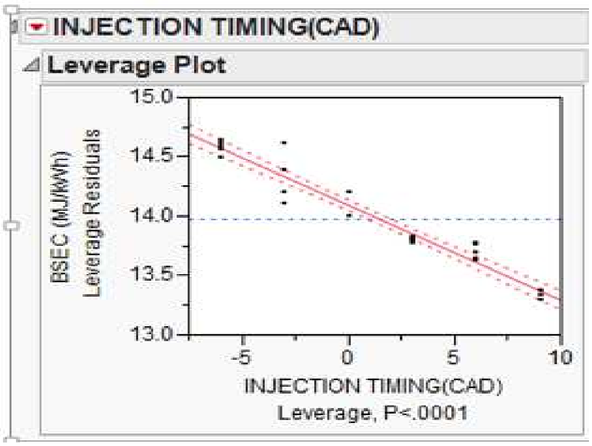

Figure 1: JMP 10 BSEC Leverage Plots for Injection Timing

For a PKOME fuelled engine the p-value (0.0001*) in table shows there is a significant effect of varying injection pressure on BSEC. Figure 2 indicates that the higher the injection pressure the lower the fuel consumption. BSEC for PKOME decreased all the way from 15MJ/kW h to 13MJ/kW h at 150 and 250 bar respectively.

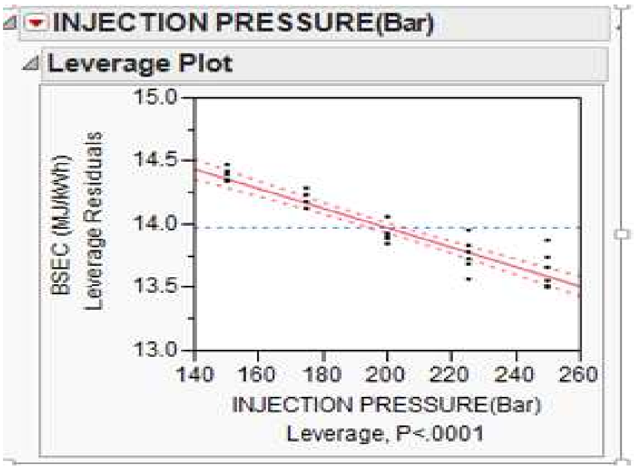

Figure 2: JMP 10 BSEC Leverage Plots for Injection Pressure

From Figure 3, it is worth noting that advancing injection timing reduces CO formation for PKOME fuelled engine while retardation however increases CO formation. This is the reverse compared with petroleum diesel engine combustion where injection advance is rather accompanied with increase CO formation. Injection retard means fuel is injected somewhat later than it normally should while injection advance means the fuel is injected earlier. Where there is

retard there is not enough time for fuel to atomize and form a homogeneous mixture for complete combustion. The fuel results in some fuel particles not finding oxygen to react with thus the high CO formation.

Injection timing therefore requires modification for use of PKOME if less CO formation is expected. Similarly increased injection pressure resulted in less CO formation. High injection pressures result in good fuel atomization and hence complete combustion.

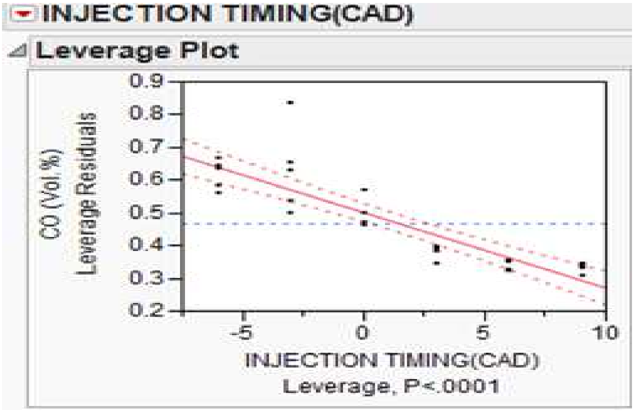

Figure 3: JMP 10 CO Leverage Plots for Injection Timing

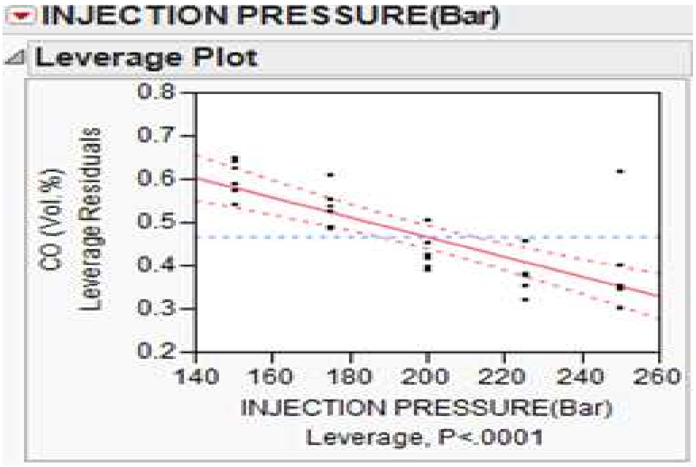

Figure 4: JMP 10 CO Leverage Plots for Injection Pressure

The parameter estimates below (Table 5) shows

Table 5: Parameter Estimates for Injection Timing & Pressure Influence on PKOME, CO Formation

Term	Estimate	Std Error	t Ratio	Prob>t
Injection timing (CAD)	-0.02301	0.002524	-9.12	<0.0001*
Injection pressure (Bar)	-0.002287	0.000366	-6.25	<0.0001*
Injection timing*Injection pressure (Bar)	0.0000819	07.139e	1.15	0.2617

That though individual engine components of injection timing and pressure had significant influence on CO formation their combined effect (0.2617) was not significant.

HC formation is usually accompanied by CO formation (Figure 3 and 4). The graph in Figure 5 and 6 shows that retardation favours HC formation while for the same reason as CO, low injections pressures also favour HC formation.

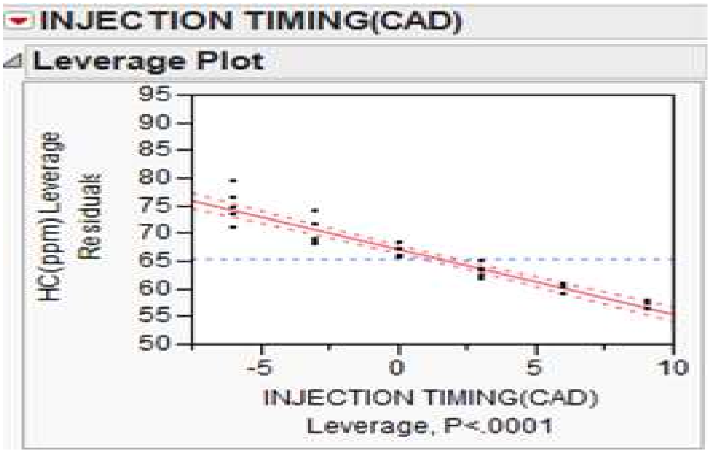

Figure 5: JMP 10 HC Leverage Plots for Injection Timing

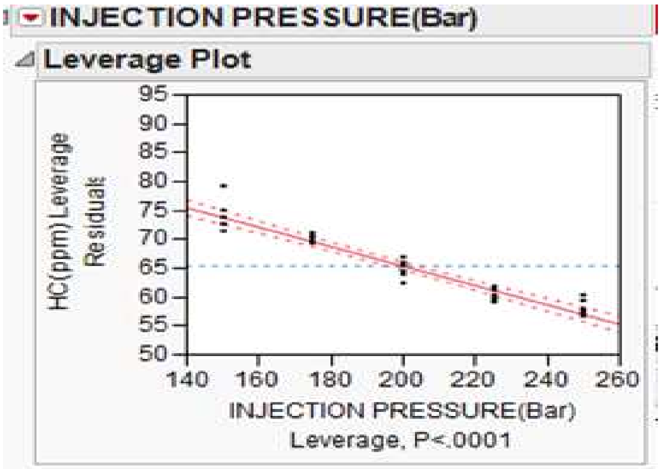

Figure 6: JMP 10 HC Leverage Plots For (B) Injection Pressure

However the parameter estimates (Table 6) depict that the combined effect of Injection timing and Injection pressure have significant influence on HC formation. Thus for a PKOME fuelled engine, to control HC formation will require adjusting both injection timing and injection pressure parameters.

Table 6: Parameter Estimates for PKOME, HC Formation

Term	Estimate	Std Error	t Ratio	Prob>t
Injection timing (CAD)	-1.173333	0.0065614	-17.88	<0.0001*
Injection pressure (Bar)	-0.168	0.009508	-17.67	<0.0001*
Injection timing*Injection pressure (Bar)	0.0109714	0.001856	5.91	<0.0001*

Oxides of Nitrogen increased linearly with injection advanced but reduced with retardation (Figure 7). Generally NOx formation is higher for biodiesel fuels than for petroleum diesel because of the excess oxygen. It is generally known that NOx emissions occur at high temperatures [37]. It is also seen that the higher the pressures the higher the NOx formation since higher pressures lead to higher temperatures. It is now well noted that an effort to reduce fuel consumption, CO, HC and NOx formation will result in increasing NOx formation and vice versa.

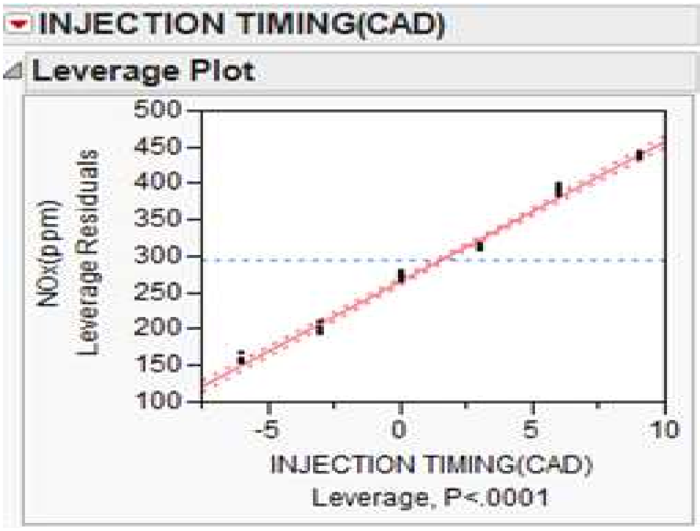

Figure 7: JMP 10 NOx Leverage Plots for Injection Timing

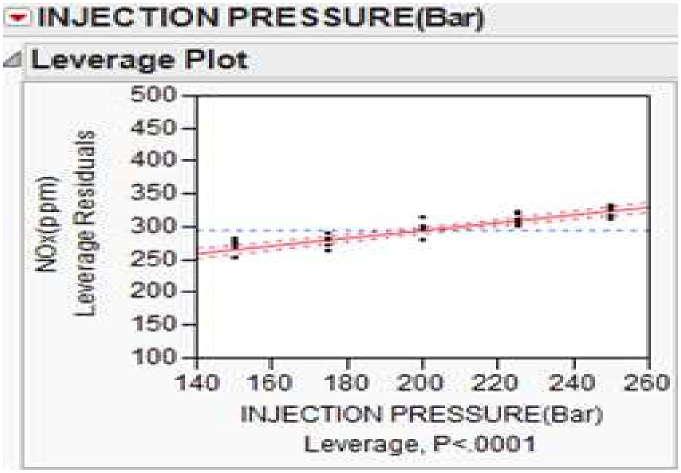

Figure 8: JMP 10 NOx Leverage Plots for Injection Pressure

Desirable Values for PKOME Engine

In this work, full factorial method based desirability approach was used for the optimization of injection system parameters (injection timing and pressure) for measured properties of BSEC, CO, HC and NOx with the help of Design Expert software (Table 7).

Table 7: Maximum Desirability Points for PKOME Engine Parameters Validated

Injection Timing(CAD)	Injection Pressure (Bar)	BSEC (MJ/Kw H)	CO (Ppm)	HC (Vol. %)	NOX (Ppm)	Desirability
3	**250**	**13.4**	**0.27**	**56**	**340**	**0.726**
3	225	13.6	0.29	58	330	0.699
0	250	13.6	0.38	58	300	0.698
-3	225	13.9	0.47	63	223	0.652
0	225	13.8	0.41	61	292	0.651
3	200	13.8	0.38	65	308	0.626
-6	250	14.2	0.49	64	179	0.611

This results were validated and agreed mostly with measured engine runs in the laboratory with an error of 0.005%. The maximum desirability was 72.6% at injection pressure of 250bar and injection advance of 3^0. However, at this desirability CO, HC and fuel consumption were at their minimum at the expense of high NOx emissions (340ppm). If NOx reduction is the goal, then the best parameter will be at 250bar injection pressure and injection retard of 6^0C.

Engine Optimization for COME Engine

Fuel consumption and emission analysis were investigated for COME as for PKOME. The results obtained for CO emissions were not different from PKOME except the p-value showed that both parameters did not influence the emissions significant.

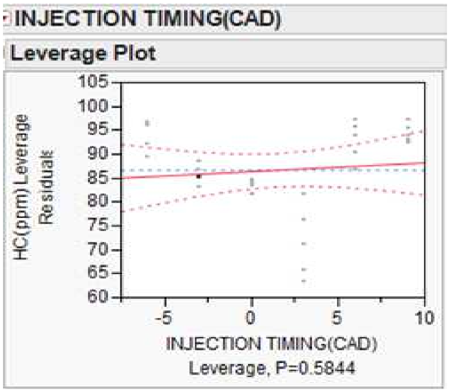

Figure 9: JMP 10 COME Leverage Plots for Injection Timing

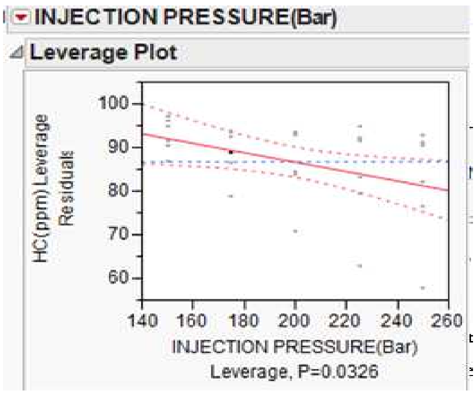

Figure 10: JMP 10 COME Leverage Plots for Injection Pressure, HC Emissions

Injection timing parameter did not have significant impact on COME engine emissions since the p-value of 0.5844 was far above the primary value of 0.05 that shows significance. Just like PKOME, while injection pressure increased, HC emissions reduced (Figure 10). The combined effect of injection timing and injection pressure was significant in HC emissions for COME. The results for BSEC though followed the same trend as PKOME showed a high significance with a p-value of 0.0014.

Desirable Values for COME Engine

Maximum desirability points were obtained (Table 8) which were validated through engine runs with error 0.05%. Engine parameters chosen for COME fuelled engine for low fuel consumption and emissions are injection pressure of 250 Bar and timing advance of 3^0C as with a high desirability of 82%.

Table 8: Fuel Consumption and Engine Emissions Data Obtained for COME

Injection Timing (CAD)	Injection Pressure(Bar)	BSEC (MJ/Kw H)	CO (Ppm)	HC (Vol. %)	NOX (Ppm)	Desirability
3	**250**	**13.8**	**0.24**	**74**	**176**	**0.82**
0	250	14.2	0.3	75	142	0.59
6	225	14.1	0.26	78	167	0.577
-3	225	14.4	0.31	79	135	0.55

At this points minimum BSEC (13.8MJ/kW h), CO (0.24ppm), HC (74Vol. %) at the expense of high emissions of NOx (176 ppm) are expected. For lower NOx emissions at the expense of other parameters, then injection retardation of 3^0C and injection pressure of 225 Bar are the optimum parameters for COME engine.

Engine Optimization for COME Engine

Fuel consumption and emissions measurements were taken according to the experimental matrix. The P-values from Table 9 indicate that the influence of injection timing on brake specific energy consumption for Jatropha biodiesel was not significant since the P-value of 0.0456 was far short of the significant value. The most significant parameter was injection pressure with a P-value of 0.0072. Thus for a Jatropha fuelled engine injection pressure need to be optimised to obtain optimum fuel consumption.

Table 9: Parameter Estimates for JCME for BSEC

Term	Estimate	Std Error	T Ratio	Prob>T
Injection timing (CAD)	-1.173333	0.0065614	-17.88	0.0456
Injection pressure (Bar)	-0.168	0.009508	-17.67	0.0072*
Injection timing*Injection pressure (Bar)	0.0109714	0.001856	5.91	0.8773

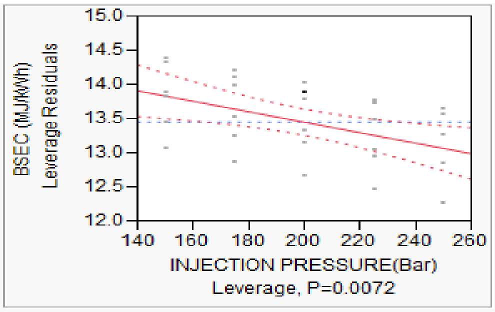

Figure 11: Rate of Brake Specific Energy Consumption with Injection Pressure Increase

It is noticed from Figure 11 that in the case of Jatropha biodiesel, there is continuous reduction in fuel consumption as the injection pressure is increased from 150 Bar to 250 Bar. The higher the injection pressure the better the chance of homogeneity in the combustion chamber and the lesser fuel is wasted. Higher pressures lead to higher temperatures enhancing combustion. Carbon monoxide emissions reduced continuously with injection advance and vice versa (Figure 12).

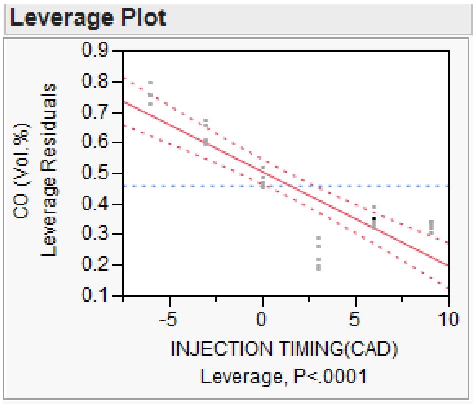

Figure 12: Carbon Monoxide Emission Trend with Varying Injection Timing

The p-value ($p<0.0001$) also proves that injection timing is very influential on carbon monoxide emissions of Jatropha fuelled engine

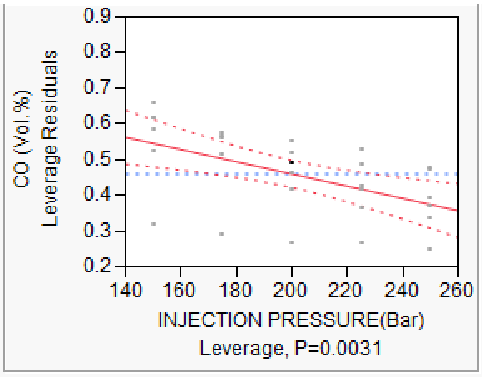

Figure 13: Carbon Monoxide Emissions with Varying Injection Pressures

In the case of injection pressure there was a significant effect but not as injection timing. As shown in Figure 13 the higher the pressure the lower the carbon monoxide formation. Higher pressures lead to higher temperatures which contributes to a more complete combustion hence the less CO formation.

With a p-value of 0.5159 the effect of injection timing on hydrocarbon formation was not significant. The effect of injection pressure on HC formation was however very significant with a p-value less than 0.0001. Hydrocarbon formation lessened continuously as injection pressure increased. The high oxygen presence in Jatropha biodiesel coupled with its associated high temperatures ensures a more complete combustion leading to less hydrocarbon formation. The combined effect of Injection timing and pressure for a Jatropha biodiesel fuelled engine was found not to be significant with a p-value of 0.9208.

Figure 14 shows that when the injection timing is advanced, the NOx emissions increase significantly. Firstly NOx formation is high in cases of high temperatures and pressures. The ballast oxygen contained in Jatropha biodiesel causes high temperatures in the combustion chamber leading to high tendencies of NOx formation. Secondly advancing injection timing means less time for fuel to be properly atomised before combustion. This it creates uneven temperature distribution leading to high pressures.

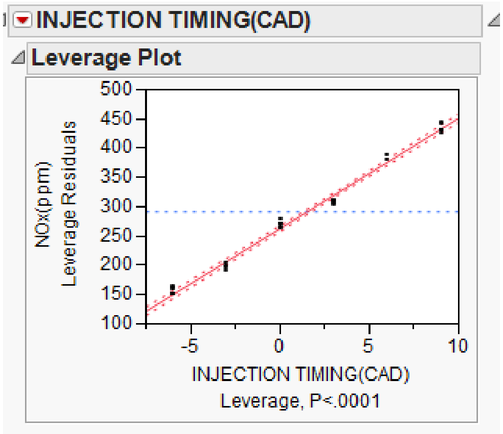

Figure 14: NOx Emissions with Varying Injection Timings

The effect of injection pressure on NOx formation was also found to be very significant as the p-value was found to be 0.0001 (Figure 15)

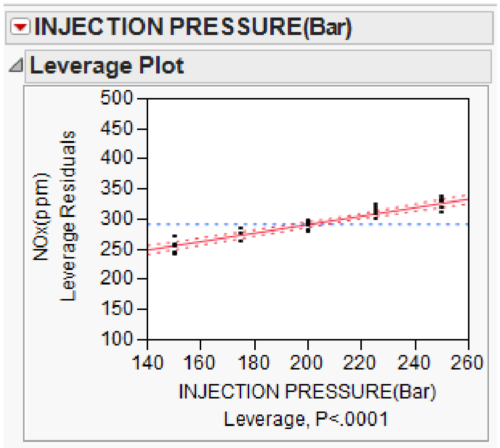

Figure 15: NOx Emissions with Varying Injection Pressures

Desirable Values for JCME Engine

Full factorial method based desirability approach was used for the optimization of injection system parameters (injection timing and pressure) for measured properties of BSEC, CO, HC and NOx with the help of Design Expert software (Table 10). The results are the validated engine values.

Table 10: Maximum Desirability Points for JCME Engine Parameters Validated

Injection Timing(CAD)	Injection Pressure (Bar)	BSEC (MJ/kWh)	CO (ppm)	HC (Vol. %)	NOX (ppm)	Desirability
3	200	12.6	0.22	60	310	0.763
-3	225	13.2	0.56	65	220	0.587

This results were validated and agreed mostly with measured engine runs in the laboratory with an error of 0.005%. The maximum desirability was 76.3% at injection pressure of 200bar and injection advance of 3^0. However, at this desirability CO, HC and fuel consumption were at their minimum at the expense of high NOx emissions (310ppm). If NOx reduction is the goal, then the best parameter will be at 225bar injection pressure and injection retard of 3^0C.

Comparison of Biodiesel Engine Performance with Petroleum Diesel

The chosen desired optimized parameters and responses for PKOME, COME and petroleum diesel are compared in Figure 16.

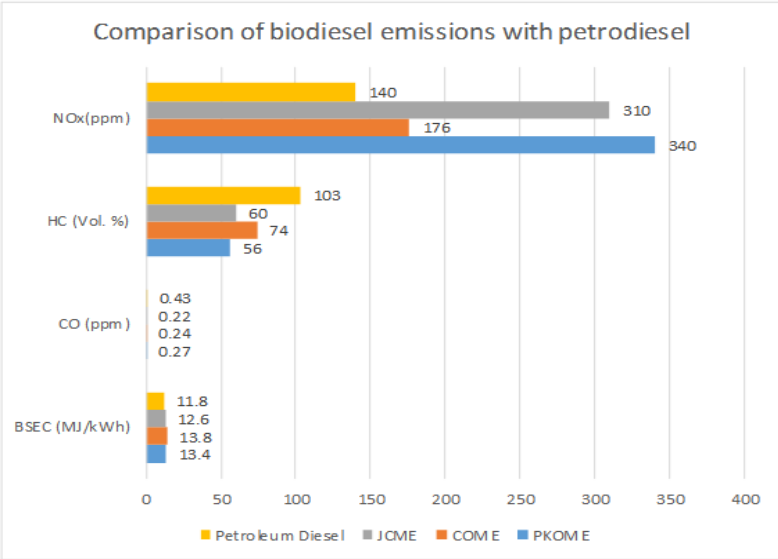

Figure 16: Comparing Optimised COME, PKOME and JCME Engine Performance Results with Petroleum Diesel

Brake specific energy consumption of petroleum diesel was better than COME and PKOME fuelled engine by approximately 14% but much closer to Jatropha biodiesel with a difference of only 0.8MJ/kW h. This is so since petroleum diesel has a higher calorific value than biodiesel. Pullen & Saeed (2014) stated that energy content is determined by the amount of HC bonds present while petroleum diesel has more of this, biodiesel has more oxygen instead (about 10% more). PKOME fuelled engine fuel consumption is better than COME by about 3%. Carbon monoxide emissions of biodiesel compared with is about 44% less than petroleum diesel engine as seen from the graph. The excess oxygen in biodiesel present more opportunities for complete combustion hence the lesser carbon monoxide emissions. COME fuelled engine at optimized parameters had lesser (11% less) CO emissions compared to PKOME. Petroleum diesel from the graph is seen to have more HC emissions (46% more) than PKOME. While COME fuelled engine HC emissions were 32% more than that of PKOME. High NOx emissions have always been recorded in published works for biodiesel due to excess oxygen causing high temperatures and hence NOx. After optimisation Petroleum diesel had 20% less NOx than COME fuelled engine and about 60% less than PKOME fuelled engine. Clearly biodiesel usage is at the expense of NOx emissions however biodiesel-biodiesel blending and EGR ratio optimisation can reduce NOx emissions.

CONCLUSIONS

- For the purpose of engine optimisation for an engine fuelled with Palm kernel oil biodiesel there is significant effect of injection pressure variation on brake specific energy consumption. The higher the injection pressure the lower the fuel consumption.
- Advancing injection timing reduces carbon monoxide and hydrocarbon formation for all three feedstocks tested. Retarding the injection timing rather increases the carbon monoxide and hydrocarbon formation. The combined

effect of injection timing and pressure however did not have significant effect on carbon monoxide formation

- The maximum desirability (palm kernel oil fuelled engine) was 72.6% at injection pressure of 250bar and injection advance of 3^0. However, at this desirability CO, HC and fuel consumption were at their minimum at the expense of high NOx emissions (340ppm). If NOx reduction is the goal, then the best parameter will be at 250bar injection pressure and injection retard of 6^0C with NOx emission of 179ppm.
- Most favourable engine parameters chosen for coconut biodiesel fuelled engine for low fuel consumption and emissions are injection pressure of 250 Bar and timing advance of 3^0C as with a high desirability of 82%. At this points minimum brake specific energy consumption (13.8MJ/kW h), CO (0.24ppm), HC (74Vol. %) at the expense of high emissions of NOx (176 ppm) are expected. For lower NOx emissions at the expense of other parameters, then injection retardation of 3^0C and injection pressure of 225 Bar are the optimum parameters with 135ppm NOx emissions.
- Jatropha biodiesel fuelled engine optimised parameters include injection pressure of 200bar and injection advance of 3^0. However, at this desirability CO, HC and fuel consumption were at their minimum at the expense of high NOx emissions (310ppm). If NOx reduction is the goal, then the best parameter will be at 225bar injection pressure and injection retard of 3^0C with 220ppm NOx emissions.

REFERENCES

1. Agarwal AK. (2007) Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Prog Energy Combustion Sci 2007; 33:233-71.
2. Escobar JC, Lora ES, Venturini OJ, Yanez EE, Castillo EF, Almazan O (2009). Biofuels: environment, technology and food security. Renewable Sustainable Energy Review 2009; 13:1275-87.
3. Aliyu B, D. Shitanda, S. Walker, B. Agnew, S. Masheiti, R. Atan (2011) Performance and exhaust emissions of a diesel engine fuelled with Croton megalocarpus (musine) methyl ester. Applied Thermal Engineering: 31 (2011) 36-41.
4. Gullison RE, Frumhoff PC, Canadell JG, Field CB, Nepstad DC, Hayhoe K (2007) Tropical forests and climate policy. Science 2007; 316:985-6
5. Hill J, Nelson E, Tilman D, Polasky S, Tiffany D. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc Natl Acad Sci U S A 2006; 103(30):11206-10.
6. Margaroni D (1998) Fuel lubricity, Industrial Lubrication and Tribology. 50(3): 108-118.
7. Ryan TW, Callahan TJ, Dodge LG (1982). Characterization of vegetable oils for use as fuel in diesel engines, Proc. International Conf. on Plaint Oils as Fuels. American Society of Agricultural Engineers 4(82): 70-81.
8. Knothe G, Steidley KR. (2007) Kinematic viscosity of biodiesel components (fatty acid alkyl esters) and related compounds at low temperatures. Fuel 2007; 86:2560–7.

9. Krahl J, Munack A, Schröder O, Stein H, Herbst L, Kaufmann A, Bünger J (2005). Fuel design as constructional element with the example of biogenic and fossil diesel fuels, Agricultural Engineering International: the CIGR J. Sci. Res. Dev. 7(EE 04 008).
10. Mofijur, H.H. Masjuki, M.A. Kalam, A.E. Atabani (2013) Evaluation of biodiesel blending, engine performance and emissions characteristics of Jatropha curcas methyl ester: Malaysian perspective. Energy 55 (2013) 879-887.
11. Bhupendra Singh Chauhan, Naveen Kumar, Haeng Muk Cho (2012) A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends. Energy 37 (2012) 616-622.
12. Ong H.C, T.M.I. Mahlia, H.H. Masjuki, R.S. Norhasyima (2011) Comparison of palm oil, Jatropha curcas and Calophyllum inophyllum for biodiesel: A review Renewable and Sustainable Energy Reviews 15 (2011) 3501– 3515.
13. Singh, Dipti Singh (2010) Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: A review Renewable and Sustainable Energy Reviews 14 (2010) 200–216.
14. Xue Jinlin, Tony E. Grift, Alan C. Hansen (2011), 'Effect of biodiesel on engine performances and emissions', Renewable and Sustainable Energy Reviews Vol. 15, pp.1098–1116.
15. Sharma Y.C, B. Singh, S.N. Upadhyay (2008), Advancements in development and characterization of biodiesel: a review, Fuel 87 (2008) 2355–2373.
16. Khatri Kamal Kishore, Dilip Sharma, S. L. Soni, Satish Kumar, Deepak Tanwar (2010) investigation of Optimum Fuel Injection Timing of Direct Injection CI Engine operated on Preheated Karanj-Diesel Blend. Jordan Journal of Mechanical and industrial Engineering Volume 4, Number 5, November 2010.
17. Laguitton, O., Crua,C. , Cowell, T., Heikal, M.R. and Gold, M.R. (2007). The effect of compression ratio on exhaust emissions from a PCCI diesel engine. Energy conversion and Management 48 (2007) 2918–2924.
18. Nwafor O.M.I (2007) Effect of advanced injection timing on emission characteristics of diesel engine running on natural gas. Renewable Energy 32 (2007) 2361–2368.
19. Mccormick Robert L, Michael S, Graboski, Teresa L, Alleman, Andrew MH and Shaine TK (2001). Impact of Biodiesel Source Material and Chemical Structure on Emissions of Criteria Pollutants from a Heavy- Duty Engine. Environ. Sci. Technol. 35:1742-1747.
20. Payri R, F.J. Salvador, J. Gimeno, J. De la Morena(2011)Influence of injector technology on injection and combustion development – Part 1: Hydraulic characterization Applied Energy 88 (2011) 1068–1074.
21. Alamu, O.J., Akintola, T.A., Jekayinfa S.O., Enweremadu,C.C. & Adeleke, A.E., 2007a, 'Characterisation of palm-kernel oil biodiesel produced through NaOH- catalysed transesterification process', Scientific Research and Essay Vol.3 (7), pp. 308-311.
22. Alamu, O.J., Waheed, M.A. & Jekayinfa S.O., 2006b, 'Effect of ethanol-palm kernel oil ratio on alkali-catalysed biodiesel yield', Fuel 87 (2008) 1529–1533.

23. Alamu, O.J., Waheed, M.A. & Jekayinfa S.O., 2008, 'Biodiesel production from Nigerian palm kernel oil: effect of KOH concentration on yield', Energy for Sustainable Development • Volume XI No. 3.

24. Jitputti Jaturong, Boonyarach Kitiyanan, Kunchana Bunyakiat, Pramoch Rangsunvigit & Peesamaj Jenvanit panjakul, (2004), 'Transesterification of Palm Kernel Oil and Coconut Oil by Difference Solid Catalysts', The Joint International conference on "sustainable energy and environment (SEE)"1-3 December 2004, Hua Hin, Thailand.

25. Ma, F. and Hanna, M.A., (1999) 'Biodiesel production: a review'. Bioresour Technol Vol.70, pp.1–15.

26. Rao P.V (2011), 'Experimental Investigations on the Influence of Properties of Jatropha Biodiesel on Performance, Combustion, and Emission Characteristics of a DI-CI Engine', World Academy of Science, Engineering and Technology, Vol.75 2011.

27. Hasimoglu C, Ciniviz M, Ozsert I, Icingur Y, Parlak A, Salman MS. Performance characteristics of a low heat rejection diesel engine operating with biodiesel. Renewable Energy 2008; 33 (7):1709–15.

28. Knothe G, Gerpen JV, Krahl J (2005), the Biodiesel Handbook, Illinois, AOCS Press.

29. Murari Mohon Roy, Wilson Wang and Justin Bujold (2013), 'Biodiesel production and comparison of emissions of a DI diesel engine fuelled by biodiesel diesel and canola oil–diesel blends at high idling operations', Applied Energy 106, pp.198–208.

30. Ayhan Demirbas (2007), Biodiesel: A Realistic Fuel Alternative for Diesel Engines. Springer, ISBN: 978-1-84628-995-8.

31. Kent Hoekman, Amber Broch, Curtis Robbins, Eric Ceniceros, Mani Natarajan (2011) 'Review of biodiesel composition, properties, and specifications', Renewable and Sustainable Energy Reviews, In press.

32. Agarwal Deepak, Shailendra Sinhab, Avinash Kumar Agarwal (2006), 'Experimental investigation of control of NOx emissions in biodiesel-fuelled compression ignition engine', Renewable Energy, Vol. 31, pp. 2356–2369.

33. Abu-Jrai a, J. Rodríguez-Fernández, A. Tsolakis, A. Megaritis, K. Theinnoi, Saleh H.E (2009) 'Effect of exhaust gas recirculation on diesel engine nitrogen oxide reduction operating with jojoba methyl ester', Renewable Energy, Vol.34, pp. 2178–2186.

34. Saleh H.E (2009), 'Effect of exhaust gas recirculation on diesel engine nitrogen oxide reduction operating with jojoba methyl ester', Renewable Energy, Vol. 34, pp.2178–2186.

35. Pradeep V, R.P. Sharma (2007) 'Use of HOT EGR for NOx control in a compression ignition engine fuelled with bio-diesel from Jatropha oil', Renewable Energy, 32, pp.1136–1154.

36. Jakeria, M.R; Fazal, M.A; Haseeb, A.S., (2014), 'Influence of different factors on the stability of biodiesel: A review', Renewable and Sustainable Energy Reviews, Vol.30, pp.154–163.

37. Willard W. Pulkrabek (2005), 'Engineering Fundamentals of the Internal Combustion Engine', Prentice Hall, upper Saddle River, New Jersey.